DYNAMIC MOTION PREDICTION AND ENERGY LEVEL DETERMINATION FOR A VIRTUAL SOLDIER'S UPPER-BODY

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Virtual Soldier Research Program

at The University of Iowa

- Funded primarily by the US Army, we conduct basic and applied research for creating new technologies dealing with digital human modeling and simulation. We are a group of 36 people (faculty, staff, scientists, engineers, clinical researchers, and graduate students) that have come together to create this new technology.

Our strengths and areas of expertise

Real-time Simulation/gaming
Real-time rendering/visualization

Human Motion Prediction
Kinematics (postures/trajectories)

Task-based kinematics
Task execution

Balance and instability
Dynamics and environment

EMG
Which muscles are active when!

Real-time dynamics
Performance

Joint Stress
Pain/injury prediction

Muscle Fatigue
Hills Models, energy

Real-time optimization
Genetics and gradient based

Clothing
Mathematical Modeling

Motion Capture
Model verification

Multi-objective Optimization
many human performance measures

Muscle contraction
FEM models

Force Feedback Control
Haptics

Motion Prediction for Various Tasks

- pulling a lever
- lifting an object
- turning a steering wheel
- pulling trigger
- moving tools
- pushing a button
- etc.

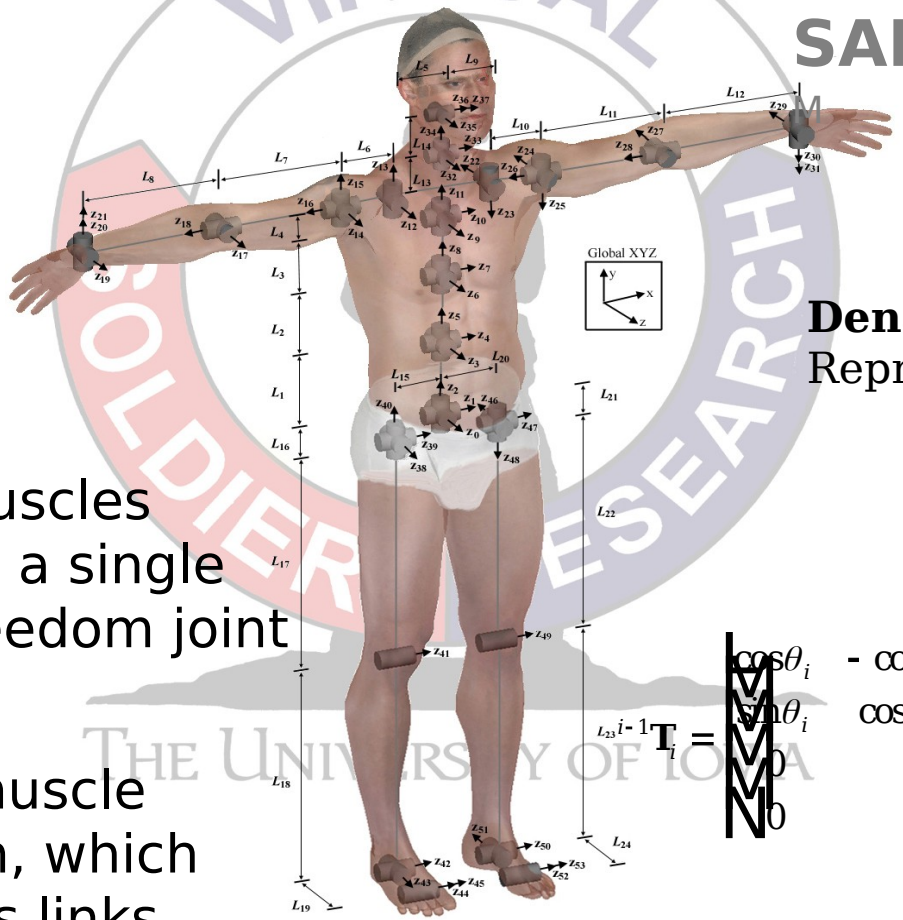
Upper-Body Motion with External Loads

Our Assumptions

- Different tasks lead to different external loads and paths (at the end-effector, or hand)
- Different external loads lead to different motion/posture
- Human acts in such a way as to minimize certain cost functions – human performance measures.

Generalized Coordinates and Generalized Torques

SANTOS^{TM}



- Multiple muscles contribute to a single degree-of-freedom joint motion.
- Complex muscle configuration, which also varies as links move.

Denavit-Hartenberg Representation

$$\begin{bmatrix} \mathbf{x}(\mathbf{q}) \\ 1 \end{bmatrix} = {}^{0}\mathbf{T}_{n}(q_1,\ldots,q_n) \begin{bmatrix} {}^{n}\mathbf{x} \\ 1 \end{bmatrix}$$

$${}^{0}\mathbf{T}_{n}(\mathbf{q}) = {}^{0}\mathbf{T}_{1}(q_1)\,{}^{1}\mathbf{T}_{1}(q_2)\ldots{}^{n-1}\mathbf{T}_{n}(q_n)$$

$${}^{i-1}\mathbf{T}_{i} = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Muscle Joint System

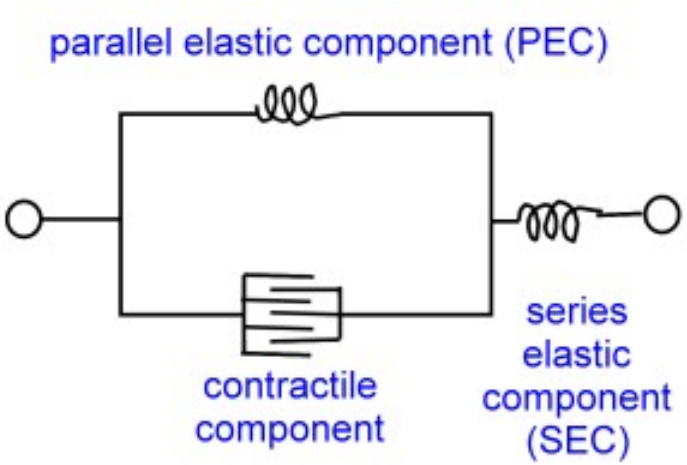
- Muscle (and tendon) = contractile components + elastic components
- Examples:

Hill's muscle model (Hill, 1938),

Zajac's Muscle model (Zajac, 1989)

- Joint torque vector due to muscle elasticity:

$$\boldsymbol{\tau} = -\mathbf{K}\left(\mathbf{q} - \mathbf{q}^{N}\right)$$

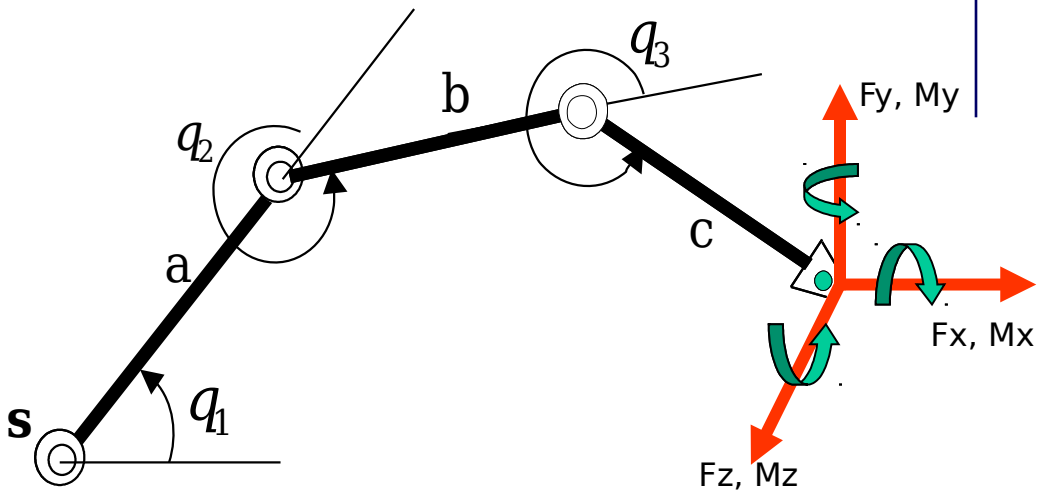


Typical Muscle Model

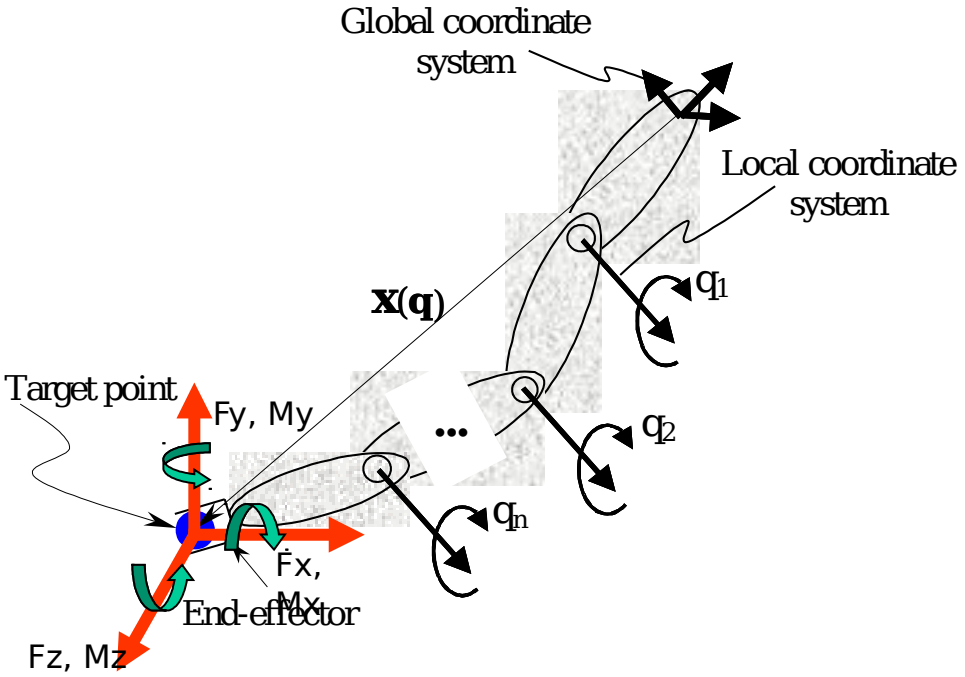
Joint Torque Prediction

- Equation of motion derived from Lagrangian mechanics

- General external loads are applied at the end-effector (hand)



Dynamic Equations of Motion



$$\tau = \underbrace{M(q)\ddot{q}}_{\text{mass\&inertia matrix}} + \underbrace{V(q,\dot{q})}_{\text{Coriolis\& Centrifugal}} + \underbrace{\sum_i J_i^T m_i g}_{\text{gravity forces}} + \underbrace{\sum_k J_k^T F_k}_{\text{external forces}} + \underbrace{K(q - q^N)}_{\text{muscle elasticity}}$$

Muscle Energy Consumption

"Total muscle energy consumption = Work done by joint torques + Heat"

$$E_{muscle} = W_{\text{joint}} + Q_{in}$$

Muscle Energy Expenditure Rate

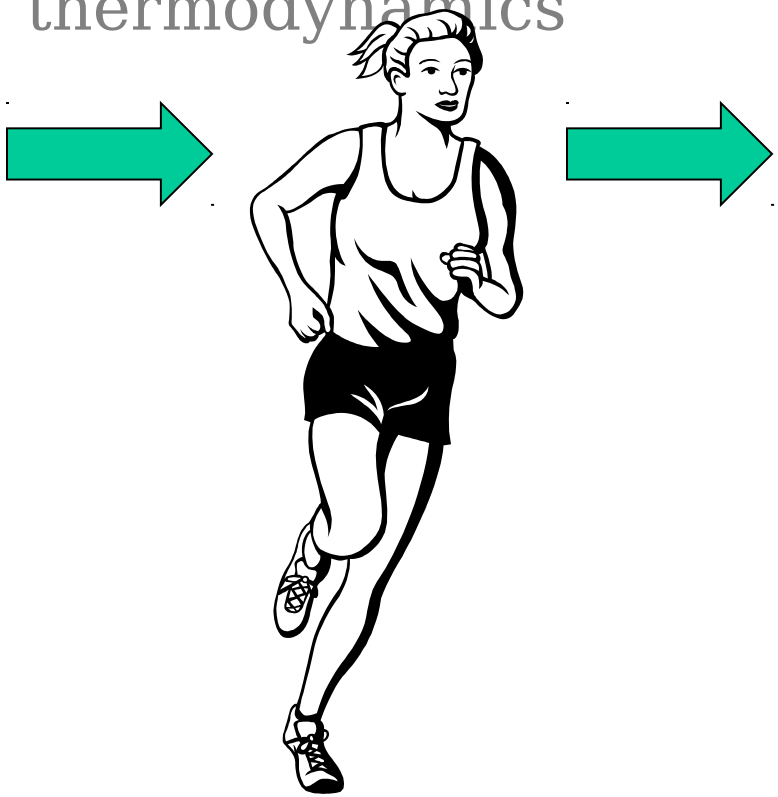
Energy rate as a function of each time instant:

$$\dot{E}_{muscle} = \dot{W}_{joint} + \dot{Q}_{in}$$

Why Energy?

Using the first law of thermodynamics

oxygen & food



mechanical work & heat

Mathematical Formulation of Energy Consumption

First law of thermodynamics: $W_e + Q_{in} = \Delta T + \Delta U$

where,

W_e : work done by external forces

Q_{in} : inlet heat energy

ΔT : change of kinetic energy of the system

ΔU : change of internal energy of the system

Muscle Energy Rate in Joint Space

$$\dot{E}_{muscle} = \dot{W}_{joint} + \dot{Q}_{in} = \sum_{i=1}^{n} \left| t_i \dot{q}_i \right| + \sum_{i=1}^{n} h_m^i \left| t_i \right| + \sum_{i=1}^{n} h_s^i \left| t_i \dot{q}_i \right| + \dot{B}$$

where,

h_m^i : coefficient of generalized maintenance heat of joint *i*

h_s^i : coefficient of generalized shortening heat of joint *i*

$\dot{B}$: basal metabolic heat rate

Realistic Upper-Body Motion Prediction

- Find Design Variables: $p_i, i = 1, 2, \ldots$
  (control points for B-Spline)

Realistic Upper-Body Motion Prediction

Optimization algorithm

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- Minimize: **Muscle Energy Consumption**

  Or muscle work $W_{\text{joint}} = \int_{t_1}^{t_2} \sum_{i=1}^{n} |\tau_i(t)\dot{q}_i(t)| dt$

(assumption: nearly constant muscle mechanical efficiency)

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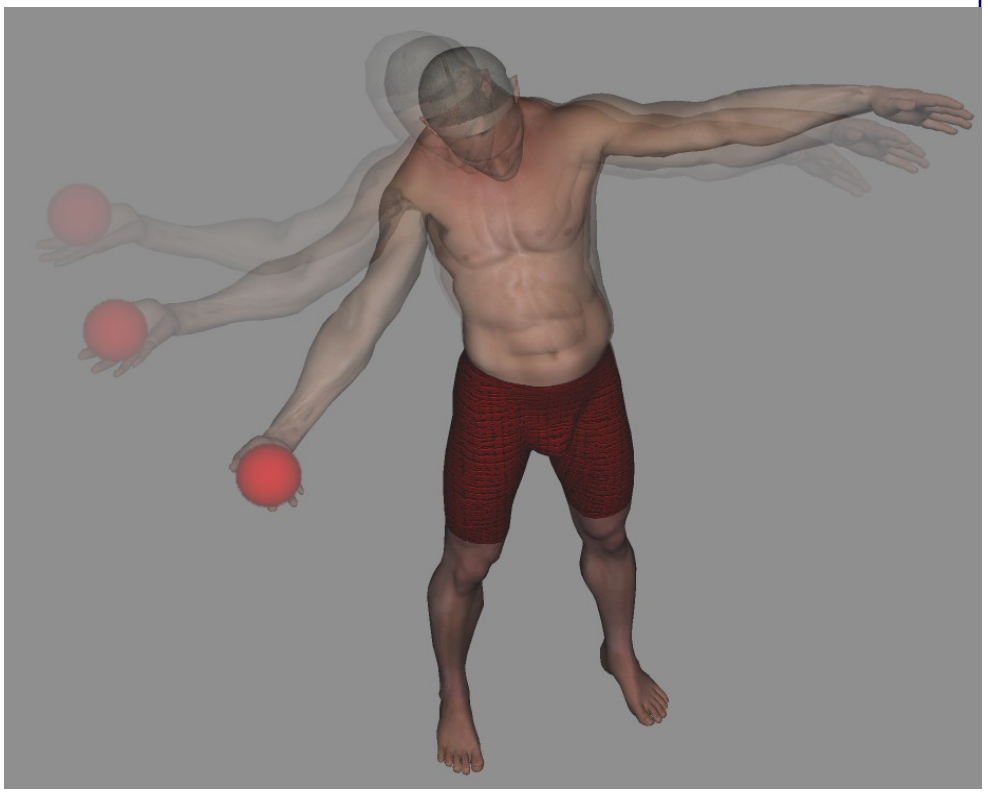
- Subject to: joint limits, torque limits, etc.

$$q_i^l \le q_i \le q_i^u$$

$$\boldsymbol{\tau}_l \le \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q}, \dot{\mathbf{q}}) + \sum_i \mathbf{J}_i^{\mathrm{T}} m_i \mathbf{g} + \sum_k \mathbf{J}_k^{\mathrm{T}} \mathbf{F}_k = \boldsymbol{\tau} \le \boldsymbol{\tau}_u$$

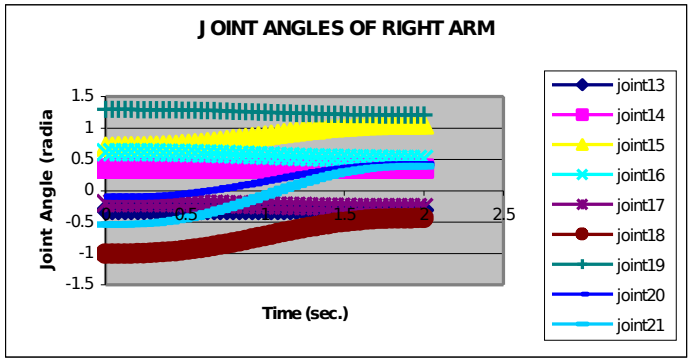
Example of Motion Prediction

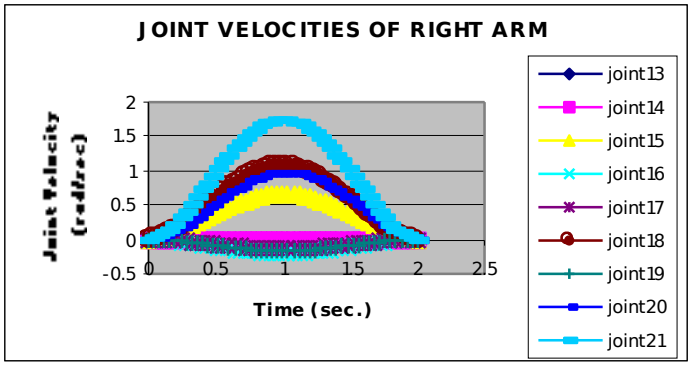
- SANTOS™ moving 5 Kg weight from initial to final position.

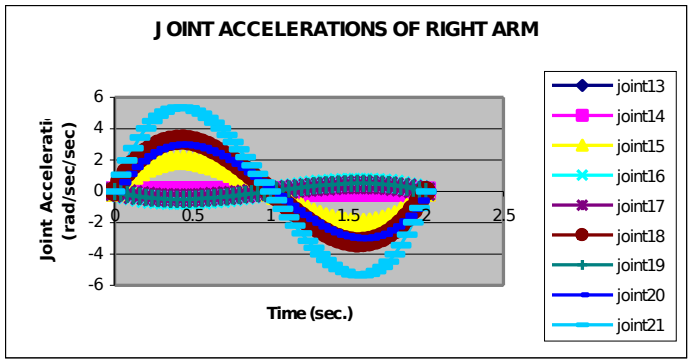


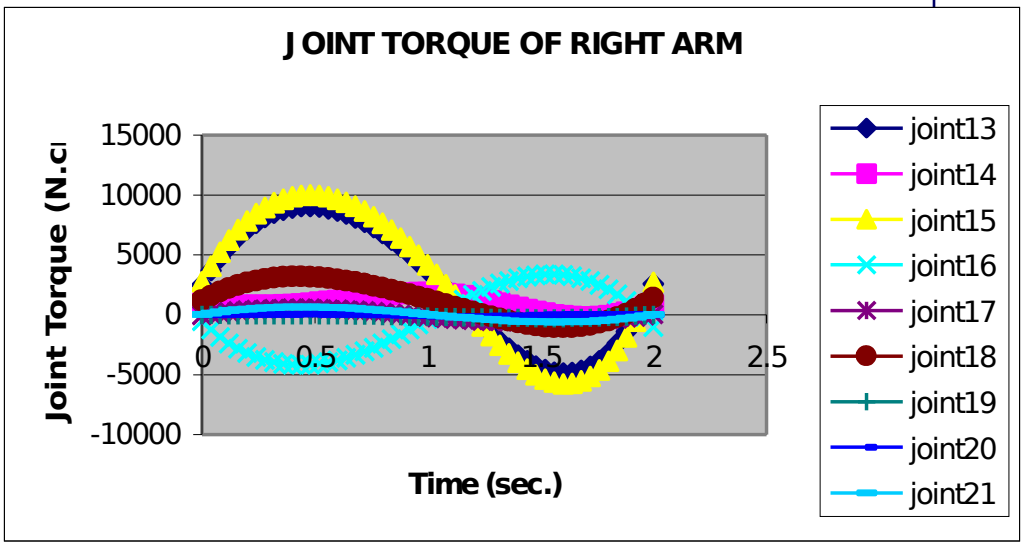
SANTOS™ moving an object

Inverse Dynamics of Example Task





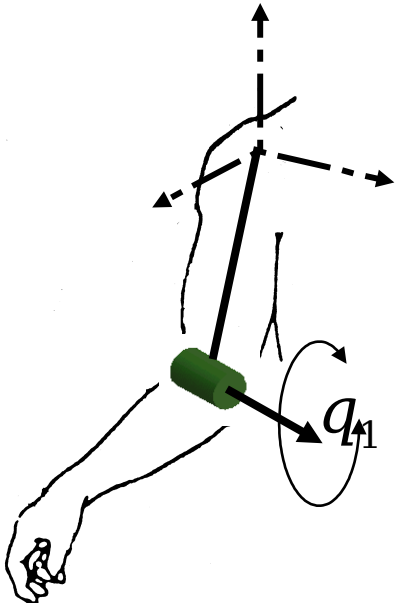


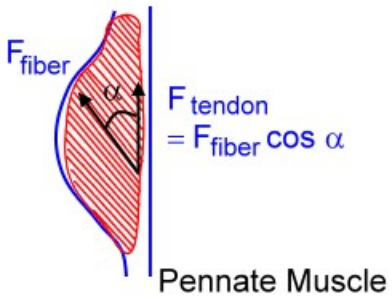


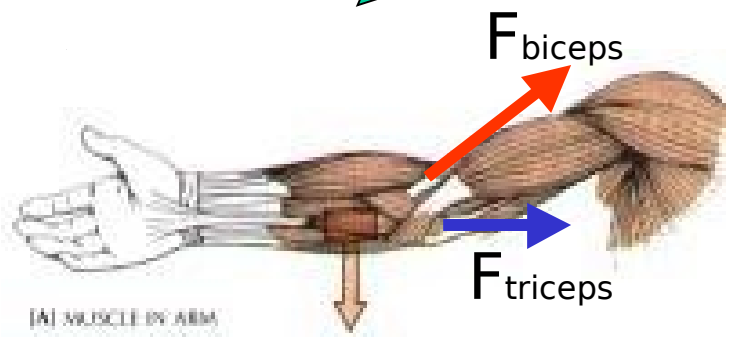
Local Biomechanical Analysis

Generalized joint torque from Inverse Dynamics

(global motion analysis)

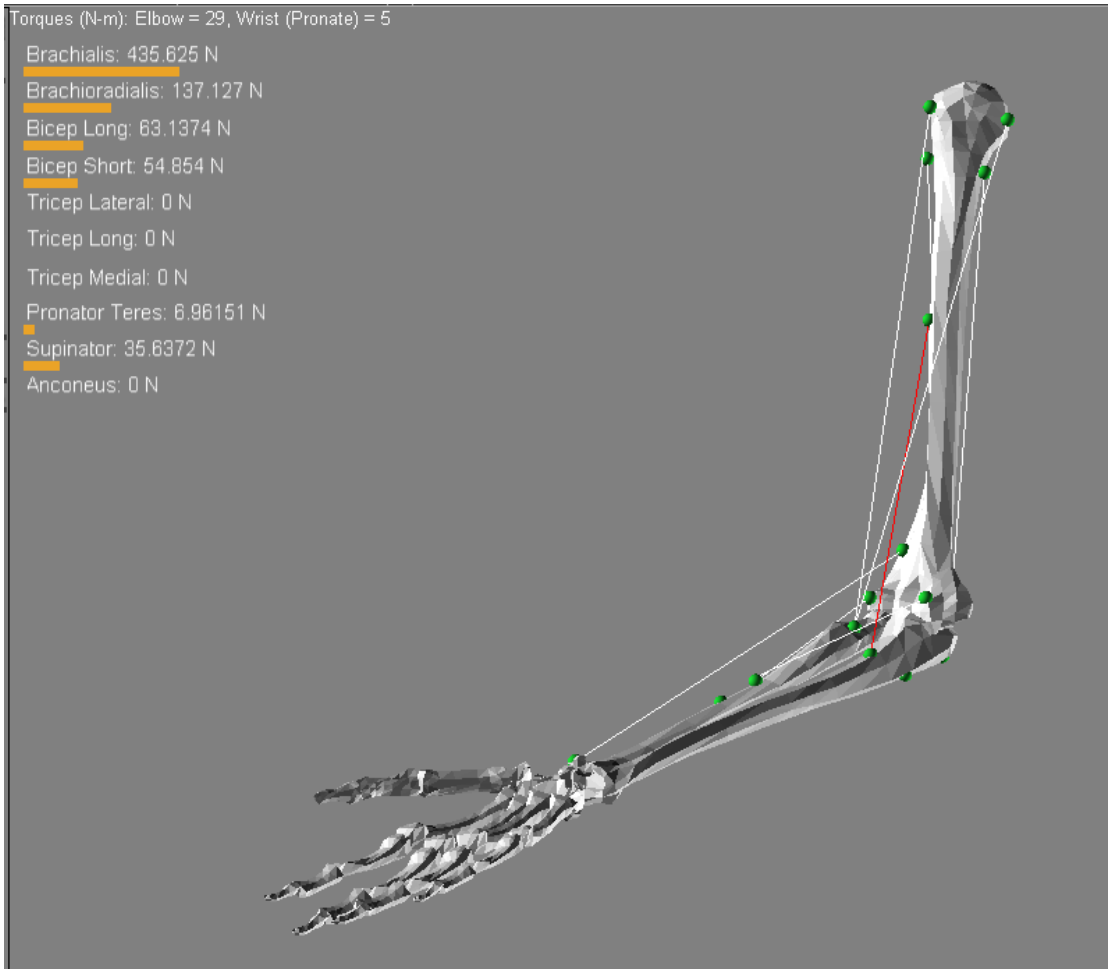




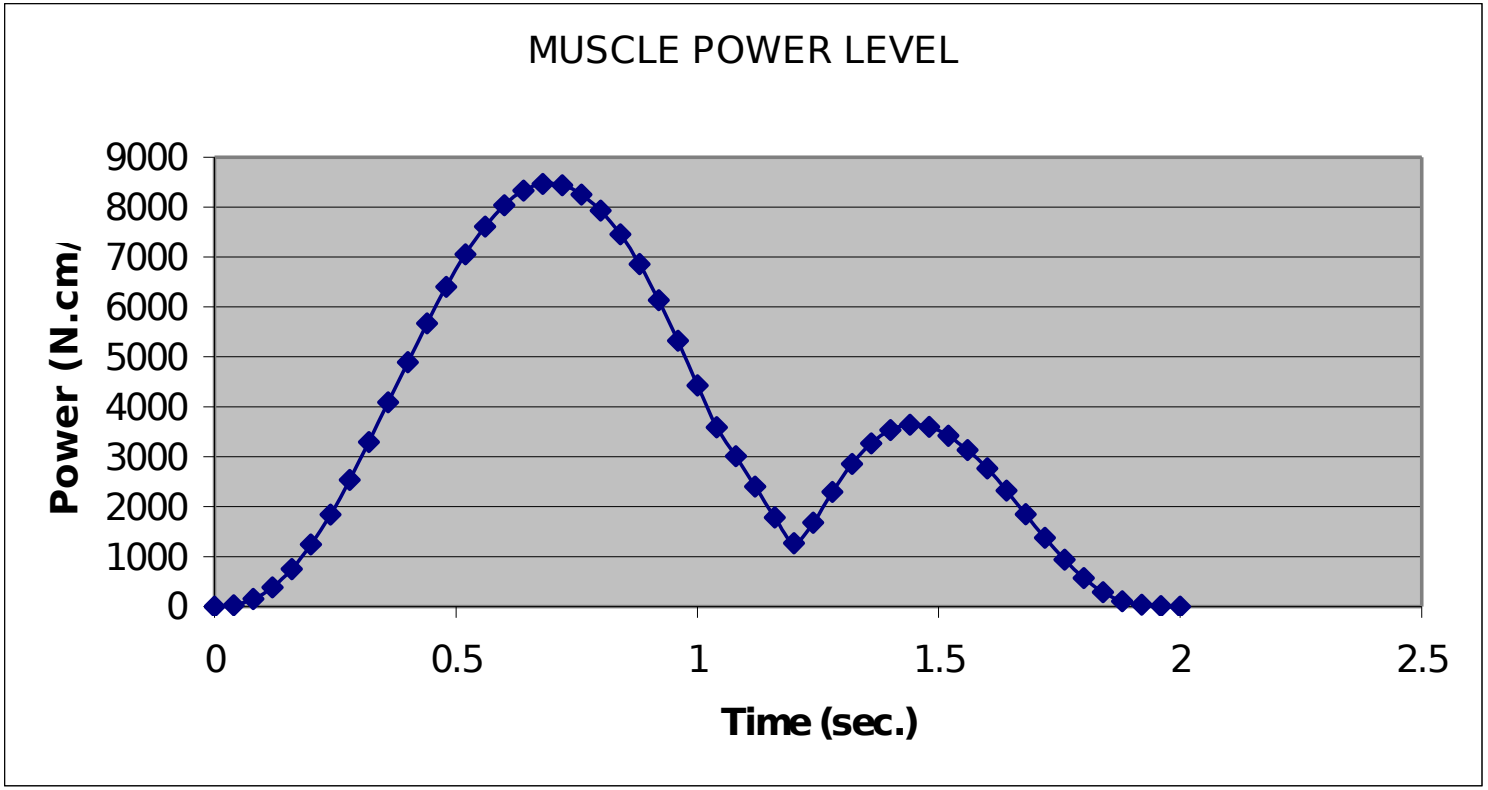


Muscle force distribution and configuration
(local biomechanical analysis)

Muscle force Distribution


Torques (N-m): Elbow = 29, Wrist (Pronate) = 5
Brachialis: 435.625 N
Brachioradialis: 137.127 N
Bicep Long: 63.1374 N
Bicep Short: 54.854 N
Tricep Lateral: 0 N
Tricep Long: 0 N
Tricep Medial: 0 N
Pronator Teres: 6.96151 N
Supinator: 35.6372 N
Anconeus: 0 N

Predicted Joint Mechanical Power



Joint mechanical power profiles for the example task

Prediction of Physiological Indexes

- Muscle Power Level
- Energy Consumption

- ✓ Heart Rate
- ✓ Body Temperature
- ✓ Blood Pressure
- ✓ Water loss
- ✓ etc.

Monitoring Human Performance Measure

- Energy (Power)
- Discomfort
- Muscle fatigue
- Instability
- Effort
- Cardiovascular fatigue (heart rate)
- Biomechanical stress
- Etc.

Conclusions

- Developed realistic human model called Santos™ with 89 degrees of freedom.

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- Derived dynamic equation of motion and energy consumption formulation in joint space.
- Prediced realistic human motion based on energy minimization (less muscle fatigue).
- Predicted joint torques and energy rate for biomechanical and physiological analysis.

Thank you

Motion/Posture prediction

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